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THE PRESENT STATUS OF THE PROBLEM OF STELLAR EVOLUTION.

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Stellar evolution—the order of development of worlds so huge and so remote that the mind fails utterly to realize their dimensions, the laws of a progress so slow as to be beyond detection in any individual case—this is one of the problems which astronomy has set itself to solve. And the attempt is not so audacious, nor the solution so impossible, as might at first appear. Many lines of research once seemingly unrelated and independent are now seen to be convergent, some have already merged. Attempts at correlation have become increasingly numerous of late and are passing from the realm of conjecture into that of reality. Such, for instance, is the close relationship of spectral class with color index, and with radial velocity.

The advance upon the problem has been rapid enough in the past few years that it is not unprofitable to assemble the facts now at hand, take note of the position already reached, and inquire as to the outlook. What are the points of attack? What data have we upon which to base a discussion of the question? In this connection, we find the following investigations in progress, or completed at the present time: the classification of the spectra of the stars; the origin and sequence of the spectral lines of these classes; the variation in wavelength of certain lines with change in class; color index, or the difference between the visual and photographic magnitudes of stars; stellar temperatures and intrinsic brightness; proper motions, parallaxes, and absolute magnitudes; radial velocities; spectroscopic binary systems; star drifts.

In the spectra of the stars we have, obviously, a means of determining differences among them. Could we obtain spectra of high enough dispersion, and could we interpret the phenomena we find, there is little which we could not read off, from its spectrum, of the constitution of a star and of the conditions prevailing in its atmosphere. A thorough-going classification of stellar spectra is accordingly one of the first points of attack in the problem.

The great majority of stellar spectra fall into four well-marked groups, first defined by SECCHI,[1] well-marked as to their general characteristics but forming a sequence by the blending of one group imperceptibly into the next—except in the case of Type IV, between which and Type III the transition is not so evident. We have first the spectra of the simplest type, with a continuous spectrum marked by absorption lines of hydrogen only, or of hydrogen and helium. These merge, through the gradual increase in strength of the metal lines, into spectra of Type II, wherein the metals predominate. These in turn give way to bands or flutings indicative of chemical combination among the elements of the stellar atmosphere. Two sorts of flutings appear, differing in source, and marking Types III and IV. Aside from these spectra, we have a fifth type, suggested by PICKERING—spectra in which the continuous background is marked by broad and faint bright bands, most of which coincide with the lines of hydrogen and helium. We have also the spectra of nebulæ, of which but little is known as yet, and the spectra of the Wolf-Rayet stars marked by both bright and dark lines. Recent classifications, notably those of Harvard[2] and of LOCKYER,[3] are more detailed and inclusive than SECCHI's. They do not, however, run counter to it, nor to one another in the matter of group boundaries; but they do differ as to the order in which these groups shall follow one another, as, whether the helium stars (Harvard B) shall fall near the beginning or near the middle of the evolution curve. The question here becomes co-extensive with that of evolution itself, and, in discussing it further, we need the data supplied by the other lines of research.

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[1] Outline given, YOUNG. "General Astronomy."
[2] *Harvard Annals*, **28** (II), 135, 1901.
[3] *Philosophical Transactions*, **184** (A), 675, 1892.

Laboratory research gives us much valuable information as to the origin of the spectral lines marking these classes and the interpretation of the differences in behaviour to be observed among them. As our knowledge of the laboratory conditions producing these differences grow, we can proceed to a tentative statement as to the conditions which prevail in stellar atmospheres. Take, for example, the nature of the enhanced line, and the conditions of temperature, pressure, and electrical intensity governing its appearance. What is the enhanced line, and what does its presence in a spectrum imply? As is well known, the spectrum of an element as seen in the electric spark differs considerably from that obtained in the arc, both in the wave-lengths of the lines present and in their relative intensities. The difference may be stated as follows:[1] Suppose we photograph the spectrum of, say, the titanium arc. Suppose next, we photograph the same region of the spark spectrum, giving it such an exposure that most of the lines will be equal in intensity to the lines in the arc spectrogram. Comparison of the two plates will show that in the spark spectrum there are strong lines present which are very faint or wanting altogether in the arc spectrum. Such lines as are relatively strengthened in the spark spectrum are called "enhanced" lines. The presence of the enhanced lines of the metals in a star's spectrum indicates that the conditions prevailing in the stellar atmosphere differ in certain essentials from those prevailing in other stars whose spectra show, not the enhanced, but the arc, lines of these metals. What the essentials are, we are coming to know more and more definitely.

That enhanced lines are perhaps dependent slightly upon temperature, and to a much greater extent upon electrical conditions, has been shown by KING[2] in his experiments with a thin-walled electric furnace. Again, the shift of enhanced lines relatively to arc lines has been investigated by GALE and ADAMS.[3] Particularly significant, along a different line of laboratory research, is FOWLER's success in obtaining a new hydrogen series[4] (at least one line of which is one hitherto

[1] *Lick Observatory Bulletin*, IX.
[2] *Astrophysical Journal*, **37**, 119, 1913.
[3] *Astrophysical Journal*, **35**, 10, 1912.
[4] *Monthly Notices Royal Astronomical Society*, **73**, 62, 1912.

unidentified line in stellar spectra), as being another step forward in the task of reproducing in the laboratory the conditions existing in the stars.

The thorough study of solar conditions now in progress at many stations is illuminating in the application of its results to stellar spectra. In the chromosphere are found the lines characteristic of stars from Classes B to F, helium, hydrogen and the enhanced lines of the metals.[1] In the spectrum of sun-spots, on the other hand, is found a close analogy to stellar spectra of Class K[2]. The possibilities here suggested for the interpretation of stellar conditions from the detailed study of these spectra on the large scale which is now possible is enormous.

Closely allied to these investigations is the variation in the wave-lengths of many stellar lines, detected by ALBRECHT.[3] Great numbers of stellar lines, on the scale usually employed, are in reality blends of two or more components. These components differ from one another in source, intensity and character, and with changing conditions in the stars they naturally change differently, possibly even in opposite directions and to the extent that one shall almost disappear while another increases greatly in intensity. The effect upon the apparent stellar line is to shift its center in the direction of the strengthening component. The shift is measurable, and evidently furnishes another criterion whereby we may judge of the conditions prevailing in each star. Curves obtained by platting wave-length against spectral type, on the assumption that the intervals F to G, G to K, K to M, are equal, check the value of these intervals, and justify the assumption. Again, "comparison with sun-spot lines indicate strongly that physical conditions as we pass from F to the M type vary roughly in the same direction as from the Sun to sun-spots." We shall refer to this again.

PARKHURST and JORDAN[4] have followed up a different line of attack, opened by PICKERING in the Harvard Photometry,[5] through their investigations, by photographic methods, of the

[1] *Lick Observatory Bulletin*, Thesis, P. W. MERRILL and E. P. WATERMAN.
[2] *Astrophysical Journal*, **30**, 86, 1909; **24**, 69, 1906.
[3] *Astrophysical Journal*, **24**, 333, 1906; **33**, 130, 1911.
[4] *Astrophysical Journal*, **27**, 169, 1908; **36**, 169, 1912.
[5] SEE, *Lick Observatory Bulletin*, **6**, 125, 1910.

visual and photographic magnitudes of stars. By means of plates sensitized for the visual rays, and with the exercise of proper precautions, they arrive at visual magnitudes which, "compared with visual and photographic magnitudes found at Harvard, Potsdam, and Greenwich, show systematic differences, but a reasonable degree of agreement." The two series, taken one upon red-sensitive and the other upon ordinary plates, furnish "a practically simultaneous determination of visual and photographic magnitudes free from most of the uncertainties of visual methods." Moreover, "definite color intensities (i. e., the difference between visual and photographic magnitudes), correspond in general to definite spectral types. While this may or may not give us much information as to stellar conditions in specific cases, it does furnish "a possible method of determining the spectrum of stars too faint for the ordinary telescope." It offers also an independent check upon the values of the spacing of the Harvard classes, with which the color intensities are compared.

The question of stellar temperatures is another fairly new and promising line of investigation. WILSING,[1] HEPPERGER,[2] NORDMANN,[3] and ROSENBERG[4] have each published a series of temperatures for the stars relative to that of the Sun. These determinations are not yet as satisfactorily established as is desirable, but they are in fair agreement among themselves, and in entire harmony with the sequence of temperatures derived by ADAMS from the comparison of stellar and sun-spot spectra, by ALBRECHT, and by LOCKYER from the relative strength of enhanced and arc lines in stellar spectra. The absolute temperatures derived have been based in each case upon measures made with a photometer or from the spectrum, of the difference in the intensities of the red, yellow and blue light emitted by the stars. From these differences, expressed in magnitudes and reduced to the Sun as standard, are derived temperatures relative to that of the Sun. NORDMANN goes farther, and investigates the intrinsic brightness of these stars, deriving an upper limit for the value of the absorption

[1] *Astrophysical Journal*, **32**, 130, 1910.
[2] *Akad. Wiss. Sitz. Ber.*, **119**, 2a, 197, 1909.
[3] *C. R.*, **149**, 557, 1038, 1909; **150**, 669, 1910.
[4] *Astronomische Nachrichten*, **193**, 358, 1913.

of radiation in their atmospheres from that of the absorption in the solar atmosphere. Another method of finding the density of stellar atmosphere has been applied by ADAMS[1] to some of the brightest stars. It is based upon the difference already referred to, in the shift under pressure of arc and enhanced lines, a definite relative shift corresponding roughly to a definite pressure. Through measures of spectra of unusually high dispersion, it was possible to detect a difference in shift between the two sets of lines, upon which to base an estimate of the pressures prevailing in the atmospheres of these stars. A comparison of results from the two methods is unfortunately impossible since the same stars were not used in the two investigations.

The outlook in the field of parallaxes and absolute magnitudes is not so promising. The direct determination of parallax is beyond the limits of our instruments at present, except in the case of a comparatively small number of stars, and the data here is meager. From the absolute magnitudes of those stars whose parallax is known, the existence of two great divisions in the stars is suspected by HERZSPRUNG, one of stars of high and the other of low intrinsic brilliancy, and named by him "giant" and "dwarf" stars. Too many inferences should not be drawn from these results until they have been confirmed by many more facts. A recent paper by RUSSELL[2] gives an optimistic statement of the outlook, however.

The increase of peculiar radial velocity with advance in type is now well established by the work of CAMPBELL,[3] the peculiar radial velocity being the velocity after correction for the Sun's motion through space has been made. As we progress from Class B through A, F. G., and K to M, we find the average velocity for the class increasing steadily, from 6^{km} per second for B to 17^{km} for M. Planetary nebulæ rank even higher, with an average of 25^{km} (the results of visual observations made by KEELER). The great nebula in *Orion*, on the other hand, in contrast with the planetary nebulæ, were found to have a (peculiar) radial velocity differing but little from zero. The character of its spectrum, together with the

[1] *Astrophysical Journal*, **33**, 64, 1911.
[2] *Proceedings of the American Philosophical Society*, 51, 1912.
[3] *Lick Observatory Bulletin*, **6**, 125, 1910.

fact that large nebulous areas are associated with stars of Classes O, B, and A, never with Classes G, K, M, and N, confirms the placing of these unformed nebulæ at the beginning of the evolution scheme. Peculiar radial velocity seems to offer a definite means of fixing the place of a star in the scheme of evolution.

Of a similar nature is the relation of the number of spectroscopic binaries, and their period, to spectral class.[1] The percentage of binaries thus far known among stars of Class B is far higher than for any other class, and decreases steadily as we advance toward M. This preponderance of "early class" binaries may, however, be due to their greater range and shorter periods. Time will show whether there be not as many among stars of the "later " classes. Hence this percentage is not of so much value in the problem as is the sequence shown in the periods and eccentricities between B and M. At the same time, the period and eccentricity of orbit increase with type. Periods of a day or less are confined to Classes B and A; those of 27 years and over to F and succeeding classes; in Class B but one period longer than 75 days has been found; in Classes G to M nothing shorter than 100 days.

Finally, we have the evidence, already referred to, of the association of the nebulous regions with stars of Classes O, A, and B, but never with those of Classes G, K, M, and N. When we see such "early class" stars either surrounded by nebulosity, as are the *Pleiades,* or close neighbors of an extended nebulous region, we must feel that the circumstantial evidence, at least, is strong that here we have stars in the making.

So much for the data upon which to base a theory of evolution. We now return to the question of the proper sequence of the stellar spectra. Two opinions are held, as has been said, as to the order. In the one, the order of evolution is that of a constantly cooling body,—stars of highest temperature and greatest intrinsic brightness being the earliest representatives, stars of relatively low temperatures the latest. This order coincides with that of the Harvard classification and is substantiated by the evidence offered by each of the investigations outlined. On the other hand, we have the order represented

[1] *Lick Observatory Bulletin,* **6**, 17, 1910.

by LOCKYER's classification, in which the classes are arranged along a curve of temperature which begins with stars of relatively low temperature, ascends to a maximum in the hydrogen stars, and descends once more to low temperatures. The stars on the ascending branch of the curve differ from those on the descending branch (LOCKYER),[1] (1) in the greater continuous absorption in the violet and ultra-violet, especially at low temperatures; (2) in the relative thinness of the hydrogen lines at high temperatures; (3) in the greater thickness and intensity of the metal lines throughout; (4) in the relatively greater thickness of the lines of helium at the temperatures at which they appear. The case for this arrangement has been put by RUSSELL:[2]

"Assuming a star grows denser as it advances in evolution, that it is in equilibrium under its own gravitation and without sensible external disturbance, that the material in it behaves like the gases with which we are familiar,—it has been shown by RITTER and others that such a star will grow hotter as it contracts until its density reaches a critical value probably between those of air and water, and nearer the latter. The temperature then reaches a maximum, and later decreases. Stars whose surface temperature has a value less than maximum will be of two kinds: one early in evolution, of rising temperature, large diameter, and low density; the other, late in evolution, of falling temperature, small diameter and high density. The former will give out many times more light. As contraction proceeds, stars having angular motion will break up into pairs, those formed first having the longest periods. The farther evolution proceeds, the greater will be the proportion of such pairs among the whole number of stars. Periods less than a day or two cannot arise unless the density is near or beyond the critical density. The proportion of these is greatest for Type B, and least for K and M. Short periods are confined to Types B and A; systems of great mass are almost all of Type B. The relation between period and eclipse-duration in binaries of the *Algol* type (Types B and A) show that their densities are close to the critical density. The distributions of proper motions among stars of a given apparent

[1] *Philosophical Transactions*, **184**, (A), 675, 1892.
[2] *Science*, **32**, 833, 1910.

brightness and spectral type shows (HERZSPRUNG) that the redder stars from G on, fall into two groups—one remote, of small proper motion and great luminosity; the other near us, of large proper motion and small luminosity. The stars of the first kind, being visible at great distances, form a disproportionately large percentage of the naked-eye stars—from 85 per cent for Type G, to 100 per cent for Type M, for which even the nearest of the stars of the second sort are invisible to the naked eye."

Many of the observed facts are explained upon this hypothesis. In the peculiar radial velocities of the stars and their relation to spectral class (on the basis either of LOCKYER's classification or that of Harvard) are facts, however, which seem at variance with it. The percentage of velocities lower than those of Class B among stars of Classes A to M on the ascending branch of the temperature curve, which is required by the sequence observed for stars of decreasing temperature, is not forthcoming. The mean velocity for Class M should be the lowest observed, since, as RUSSELL states, it is based exclusively upon stars of small proper motion and great luminosity, among the earliest if not actually the first, in point of evolution, on the LOCKYER hypothesis. The average, as we have seen, is the highest, if we except that of the planetary nebulæ.

On the whole, then, the Harvard order seems at present to be the more satisfactory. The following table gives, in brief, this order, together with such of the arguments for it as can be conveniently tabulated. The headings are self-explanatory:

Class.	Spectrum.	Average Velocity.	Binaries.
O	Bright bands. H and He present.	6.2^{km}	Very few visual binaries. One in three are spectroscopic binaries, with periods generally short and eccentricities small.
B	Absorption lines. He at maximum. H strong. Ca (K) and Mg present.		
A	Absorption lines. H at maximum. Ca (K) and Mg stronger. Enhanced lines of metals present.	10.5^{km}	Numerous visual binaries. About one in six are spectroscopic binaries; periods longer than for Classes O and B.
F	Absorption lines. H weaker. Ca (K) stronger. Enhanced lines strong. Arc lines present.	14.4^{km}	
G	Absorption lines. Ca (H and K) stronger. Enhanced lines weaker. Arc lines strong.	15.0^{km}	Numerous visual binaries. About one in six are spectroscopic binaries; periods generally long.
K	Absorption lines. Ca (H an K) very strong. Enhanced lines very weak.	16.8^{km}	
M	Absorption lines. Absorption of short wave-lengths strong. Bands present, due to chemical compounds.	17.1^{km}	Very few binaries, either visual or spectroscopic.
N	Absorption lines. Absorption of short wave-lengths strong. Bands present, due to carbon.	.....	Unknown.

Some questions remain, for which we have as yet no answer to suggest: the position of the bright-line helium stars and the Wolf-Rayet stars in the line of evolution, the relation between planetary nebulæ and the novæ, whose spectra have points of similarity. More fundamental perhaps is the question of the meaning of the hazy lines in some spectra of Classes A and F, the differences, not of the intensity of the lines but in their definition, which exist among the spectra of these classes, and which were recognized in one of the earliest Harvard classifications. In the light of the advance already made, however, and of the increase in the number and power of our instruments, we may be confident as to the final solution of this problem of the evolution of the stars.

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THE NUMBER OF STARS IN THE UNIVERSE.

By R. H. Tucker.

Many attempts have been made to form an estimate of the number of stars visible in our most powerful telescopes, or to be distinguished with the aid of photography; and speculation has been rife as to whether the universe may extend beyond the limits at which stars have been actually found to exist. It has been impossible to make counts of more than very limited areas, from which, by comparison and approximation, the estimates may be extended to larger areas, and to the whole sky.

Herschel's early set of "gauges" were counts of stars, made in various parts of the sky, with the object of forming a comparative estimate of the "richness" in many directions; thus illustrating, possibly, the form and extent of the universe of visible stars. One of his recorded estimates is five and a half million stars to the fourteenth magnitude, in the sky. But Struve, at about the same epoch, estimated twenty million of the same grade.

The most common estimate has been that fifty million would be visible in our best modern telescopes. In a recent number